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Stopped Δ-matter source in heavy-ion collisions at 10 GeV/nucleon?

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We predict the formation of highly dense baryon-rich resonance matter in Au+Au collisions at energies as provided by the Brookhaven Alternating Gradient Synchrotron (AGS). The final pion yields show observable signs for resonance matter. The Δ_{1232} resonance is predicted to be the dominant source for pions of small transverse momenta. Rescattering effects — consecutive excitation and deexcitation of Δ's — lead to a long apparent lifetime ($> 10\,\mathrm{fm}/c$) and rather large volumina (several 100 fm^3) of the Δ-matter state. Heavier baryon resonances prove to be crucial for reaction dynamics and particle production at AGS.

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Many open questions in current nuclear and particle physics require high energy and particle densities of nuclear matter to be resolved. The only way to obtain these extreme conditions in the laboratory is the study of relativistic heavy-ion collisions [1]. In particular, it has been shown that the production of very high densities requires massive systems and high energy as provided by the gold beam at the Alternating Gradient Synchrotron (AGS) in Brookhaven [2]. Several in-medium effects are eventually present at high baryon densities, such as resonance matter [3,4], mean fields due to changing quark and gluon condensates [5], the decrease of baryon masses due to chiral symmetry restoration [6], and the quark-gluon plasma. In particular, the formation of resonance matter contributes essentially to enhanced strangeness [7] and subthreshold antiproton production [8], baryon stopping, and hadronic flow effects.

Microscopic and thermal calculations have shown that pion production proceeds practically exclusively via the excitation of Δ resonances in AA reactions around 1 GeV/nucleon [15,16]. However, since the pion yield is much smaller than the number of participating nucleons, the whole dynamics is dominated by nucleon interactions.

First efforts to investigate the Δ_{1232} production in Si+Pb collisions in the ultrarelativistic regime directly via πN correlations have recently been performed by the E814 Collaboration [9,10]. In general, pions might be useful to learn about the Δ resonance [11–14] due to the almost sole decay mode $\Delta \to N + \pi$ and the particular phase-space distribution of π from Δ decays.

At higher energies ($E_{\mathrm{lab}} \approx 10$ GeV), a two-component structure in the transverse momentum spectra of pions produced in AA collisions has been observed [17,9] which is not seen in elementary pp reactions.

The low momentum component (about 50%) is dominated by Δ decay as suggested in [18,19]. In Ref. [19] the term "Δ matter" was coined to describe a system in which the Δ degree of freedom is as much excited as nucleons. The second component in 10–15 GeV/nucleon collisions, which is much stiffer than the soft one, has to be produced by another mechanism, possibly excitation of higher mass baryonic resonances as will be elucidated in this paper.

Calculations with various transport models [quark-gluon string model (QGSM), relativistic quantum molecular dynamics (RQMD), hydrodynamics] show a rich event shape differing markedly from the pure fireball scenario. Collective flow seems to be strongly reflected in the baryonic distributions (protons, deuterons). In order to take into account resonances as well as flow effects and the complex event geometry, we use in this paper the RQMD approach [20] to predict the formation of dense resonance matter in violent heavy-ion reactions. The ingredients of the model allow us to extract explicitly the role of resonance decays for the shape of the final π spectra.

The RQMD model is a microscopic phase-space approach in which the basic excitation mechanism is two-body particle scattering. Both collision partners may get excited or they may annihilate into a single s-channel state (e.g., in meson-baryon interactions). Several medium effects have been explored in the RQMD approach, e.g., mean fields [21] and string fusion into color ropes [22]. The Δ resonance is of special importance for the topics discussed in this paper. It should be noted that Δ production (e.g., in $NN \to N\Delta$), absorption (e.g., $\Delta N \to NN$ and $\pi\Delta \to B^*$), formation ($\pi N \to \Delta$), and decay ($\Delta \to \pi N$) are treated dynamically. We use nonfixed Δ masses, improved detailed balance relations for time-reversed cross sections, and the short lived nature of the Δ resonance. Low mass excitations (e.g., nonstrange baryons with mass < 2 GeV/c^2) are projected on discrete resonance states, higher mass excitations decay in a stringlike way [23]. The model describes well nuclear stopping and particle production from 1 to 200 GeV/nucleon [24,19]. Furthermore, the source size extracted from RQMD events with the Hanbury-Brown-Twiss (HBT) technique agrees well with recent measurements [25].

Figure 1 shows the transverse mass spectrum of freeze-out π^- in Au(10.7 GeV/nucleon)Au with central impact parameter ($b \leq 3$ fm) and potential interaction included. The solid line indicates the total yield whereas the other curves represent the contributions from various final resonance decays. Other pion sources (elastic meson-meson (MM) or meson-baryon (MB) scattering) are neglected.

The integrated spectrum shows a bending that is suggestive of two different contributions. The calculations

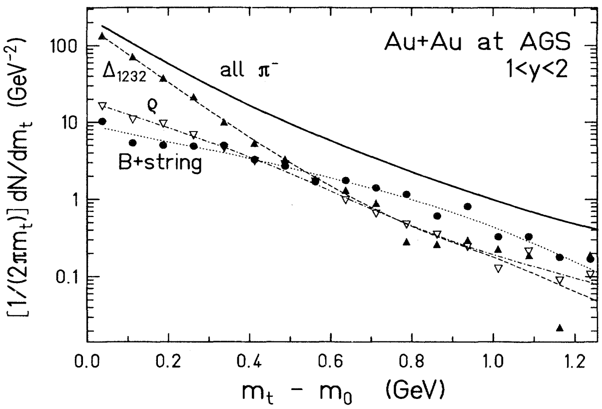

FIG. 1. Transverse mass spectra of π^- in Au+Au at midrapidity (10.7 GeV/nucleon), $b \leq 3$ fm. Total yield (solid line), pions produced by decay of Δ_{1232} (dashed), ρ (dash-dotted), and other baryons and strings (dotted). At low transverse momenta the Δ decay dominates all the other pion producing channels. For higher p_t the other baryon resonances' contribution grows and finally dominates the spectrum. The bending of the total distribution is caused by a superposition of the different shapes of the Δ contribution at low and the baryon distribution at high p_t. Thus low p_t pions might provide a useful tool to extract information about the properties of Δ matter.

give that at low transverse momenta most of the pions stem from Δ decays. Pions from heavy resonances contribute essentially at high p_t and dominate the spectrum for $m_t - m_0 > 600$ MeV. This behavior is quite easy to understand because the decay of highly excited resonances into pions will produce decay products with more kinetic energy than the decay of a Δ. ρ mesons contribute almost 10% of the total yield, higher resonances only to 5%. The decays of η, η', ω, or K^* into pions and the pion elastic scattering add up to another 15% of the total yield that will be neglected in our consideration.

The upper part of Fig. 2 shows the Δ source producing most of the final pions revealing a strong peak at midrapidity. Experimentally the dominance of Δ-resonance decays for low-p_t pions may be verified from the single spectra using a technique proposed by one of us [26]. If we turn to rapidities far from midrapidity the slopes of the distribution will change drastically with y. If the transverse momentum of a pion produced by Δ decay vanishes ($p_t \approx 0$), we will obtain a longitudinal momentum $p_z = 227$ MeV/c in the Δ rest frame (assuming a fixed Δ mass $m_\Delta = 1232$ MeV/c^2). This corresponds to a rapidity of 1.27. Thus the pion is fed into a completely different rapidity region. At rapidities with highest densities of Δ resonances we therefore expect a suppression of "ultrasoft" ($p_t \rightarrow 0$) pions. The effect just described becomes visible by plotting the ratio of the production cross section for "ultrasoft" pions with $p_t \approx 0$ and "soft" pions with $p_t \approx 150$ MeV. In the lower part of Fig. 2 the ratio of invariant production cross sections for π^+

$$C_y = \frac{\sigma_{\text{inv}}(p_t = 30 \text{ MeV})}{\sigma_{\text{inv}}(p_t = 150 \text{ MeV})} \tag{1}$$

is shown versus rapidity for central ($b < 3$ fm) Au+Au at 10.7 GeV/nucleon. The distribution shows a minimum at $y = 0$: the same rapidity where the stopped Δ source is located. Within a surprisingly small relative momentum bin ($-1 \leq y \leq +1$) we find 189 Δ's (48% of all baryons) so that it is reasonable to speak about a Δ-matter state at $y = 0$.

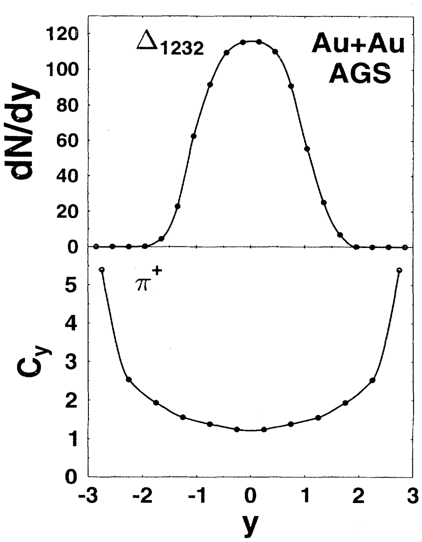

FIG. 2. Upper part: Rapidity distribution of Δ's in Au+Au at 10.7 GeV/nucleon. Only Δ's whose decay leads to a freeze-out pion are considered. There are 189 Δ's within the rapidity range $-1 \leq y \leq +1$ so that we find Δ matter at midrapidity. Lower part: Ratio of invariant cross section of π^+ vs rapidity for $p_t = 30 \pm 20$ MeV and $p_t = 150 \pm 20$ MeV. A strong minimum at midrapidity and therefore the existence of a Δ-matter state is revealed.

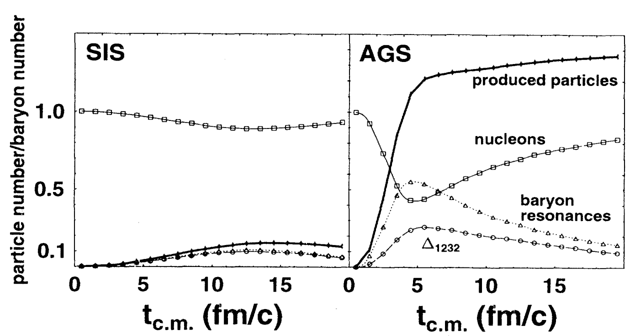

FIG. 3. Time evolution of particles in central Au+Au collisions at 1 and 10.7 GeV/nucleon, representing SIS and AGS energy ranges. Plotted are nucleons (solid line), baryonic resonances (dotted), Δ_{1232} (dashed), and all particles in the system that are not nucleons (thick solid). Left part: At SIS, only 10% of the nucleons are excited into resonances. Most of the resonances are Δ_{1232}. Thus there is no hint for a resonance matter state at SIS energies. Right part: At AGS there are more excited baryons than nucleons in the system. The Δ resonance only contributes about 50% to the resonance matter. With increasing time the Δ becomes more and more important until most of the baryonic resonances are Δ's. Thus the Δ resonance seems to decay much slower than other resonances. This behavior is due to the large $\pi N \rightarrow \Delta$ cross section that causes a consecutive excitation and deexcitation of Δ's.

Since we obtain that huge amount of resonances at 10 GeV/nucleon contributing to the final spectra, we are now interested in the dynamics of the resonances during the reaction. Figure 3 shows the time evolution of the number of resonances in central Au+Au reactions ($b < 3$ fm) at 1 GeV/nucleon (left) and 10.7 GeV/nucleon (right). Time is always taken in the center-of-momentum frame of the whole reaction. The thick solid line represents the sum of all particles in the system except nucleons. The solid line shows the nucleons while the dashed and dotted lines show the Δ_{1232} and all baryon resonances, respectively.

At AGS, between 4 and 7 fm/c the number of baryon resonances in the system exceeds the number of nucleons. In the early hot and dense stages of the reaction the main part of total particle production is performed (thick solid line). With increasing time the system becomes more and more equilibrated and the excited resonances in the system consecutively evaporate mesons. In this picture the lightest baryon resonance state, the Δ_{1232} (dashed line), proves to be a very important and interesting state. At the point of maximal excitation the Δ contributes nearly 50% to all resonances. With increasing time, only the Δ survives: its apparent lifetime ($\tau = 15$ fm/c) is much longer than that of the other excited states due to consecutive $\Delta \to \pi N, \pi N \to \Delta$ processes that are the dominant reactions in the final stage [27]. This becomes visible by switching off the Δ formation channel $\pi N \to \Delta$ which yields a decrease of the Δ lifetime to ≈ 5 fm/c.

In order to predict a resonance *matter* state we have to check whether the density of resonances and Δ's is comparable to nuclear ground state density. Furthermore, we demand the resonances to reach these densities in a rather large volume of the same order of magnitude as the reaction zone. For this, in Fig. 4 the time evolution of densities and occupied volume of baryons (solid line) and Δ's (dashed) is plotted. The reaction zone is chosen to be a $20 \times 20 \times 20$ fm^3 cube around the center of the reaction in the c.m. frame and has been discretized into small boxes of $\Delta x \Delta y \Delta z = 1$ fm $\times$ 1 fm $\times$ 2 fm. The density is calculated by averaging over the 10% boxes with the highest density. To obtain the volume all boxes with densities larger than $0.1\rho_0$ are added up. The so defined mean baryon density reaches seven times nuclear matter density. The density of Δ resonances also exceeds nuclear density and reaches $2.5\rho_0$. At the time of maximum Δ density the Δ volume becomes $V_\Delta = 500$ fm$^3 \approx \frac{1}{3} V_B$, being in the same order of magnitude as the reaction volume. The average baryon and Δ densities in this volume are $3\rho_0$ and ρ_0, respectively. Up to 10 fm/c the Δ density is still $\geq \rho_0$ while the volume becomes $V_\Delta \approx 300$ fm^3.

In order to extrapolate our results to other energy regions we plot in Fig. 5 the resonance excitation function for ^{83}Kr+^{83}Kr without potentials for Δ_{1232} (circle), N^*_{1520} (cross), Δ_{1600} (dagger), and Δ_{1700} (asterisk). The integrated number of all resonances is given by the dotted curve (triangle). The solid line (square) shows the number of nucleons. The thick solid line stands for the maximum number of all particles except nucleons. The values are taken at the time of maximum number of baryon resonances in the system. One observes that the number of excited resonances increases with beam energy. At energies $\geq$10 GeV/nucleon there are more resonances than nucleons in the system even in a light system such as Kr+Kr. Higher energies cause further but much slower increase of the resonance number, while lower energies reveal a fast falloff.

Recent claims of resonance matter formation at GSI-SIS energies [28] are scrutinized in Fig. (3) (left). Only 10–15 % of all baryons are excited to resonances, most of

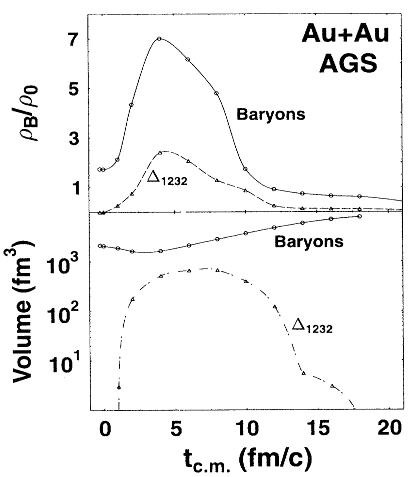

FIG. 4. Upper part: Time evolution of baryon and Δ densities. The figure shows the averaged densities over the 10% densest coordinate space boxes. The box size is chosen to be $\Delta x \Delta y \Delta z = 1$ fm $\times$ 1 fm $\times$ 2 fm. The density of all baryons reaches seven times nuclear density while the density of Δ resonances is $2.5\rho_0$. One observes high numbers of resonances at densities higher than nuclear matter density. Lower part: Volumina of baryon and Δ resonances. Only boxes with densities larger than $0.1\rho_0$ are considered.

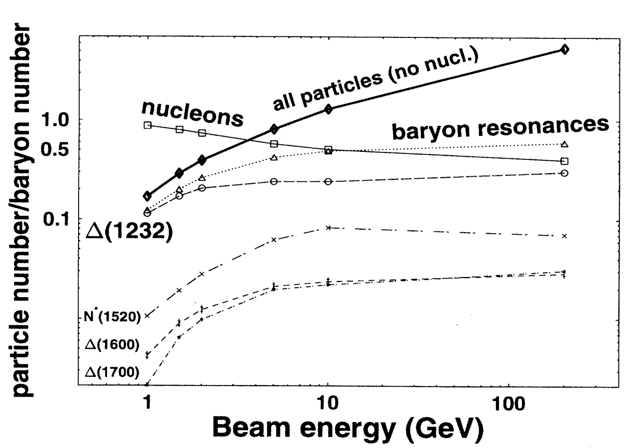

FIG. 5. Maximum number of nucleon resonances divided by total baryon number in relation to bombarding energy in central ^{83}Kr+^{83}Kr collisions ($b < 2$) calculated with RQMD in cascade mode. Calculations were done at 1, 1.5, 2, 5, 10, and 200 GeV. One easily sees the domination of the Δ_{1232} resonance in all energy ranges, although the relative contribution of the higher resonances increases with bombarding energy. Beam energies above 10 GeV show more baryonic resonances than nucleons in the system.

them Δ_{1232}, so that a description without higher resonances might be possible. But due to the smaller number of resonances nucleonic degrees of freedom are most prominent. It would be a euphemism to call such a state resonance matter [16]. The higher the energy the more heavy resonances such as N^* or Δ^* are produced, but even at CERN energies (200 GeV/nucleon) half of all resonances are Δ_{1232}. Thus the Δ remains the most important resonance state over a wide energy range, but for energies higher than 2 GeV it is necessary to take the dynamics of higher mass resonances into account.

We conclude that within the RQMD approach we predict at AGS energies the existence of a dense resonance matter state in a large volume during the early part of the reaction. Particularly, the Δ-matter state reaches densities of $2.5\rho_0$. Therefore, the investigation of the Δ propagation in a dense medium [29] is of most importance for an understanding of the AA reactions at 1 to 20 GeV/nucleon.

Higher mass baryon resonances contribute to the final pion spectra preferentially at high p_t, where they clearly exceed the Δ's contribution. Even in absolute numbers at early stages of the reaction, neglecting higher resonances leads to an overpopulation of the Δ_{1232} compared to our results. The Δ proves to be the dominant state and main source for pion production at low transverse momenta $p_t < 300$ MeV. This promises a way to get experimental information on Δ matter by analyzing especially the low-p_t pions in order to localize Δ matter in momentum space. Experimental research in the near future should be able to confirm this prediction. However, even at energies of 1 GeV/nucleon it has been shown [7,8] that higher mass resonances are crucial to understand K, $\bar{p}$, and other heavy-particle yields via multistep processes.

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